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Theoretical Analysis on Marangoni-driven Cavity Formation in Ice during In-situ Burning of Oil Spills in Ice-infested Waters - Paper Number IN43D-0096

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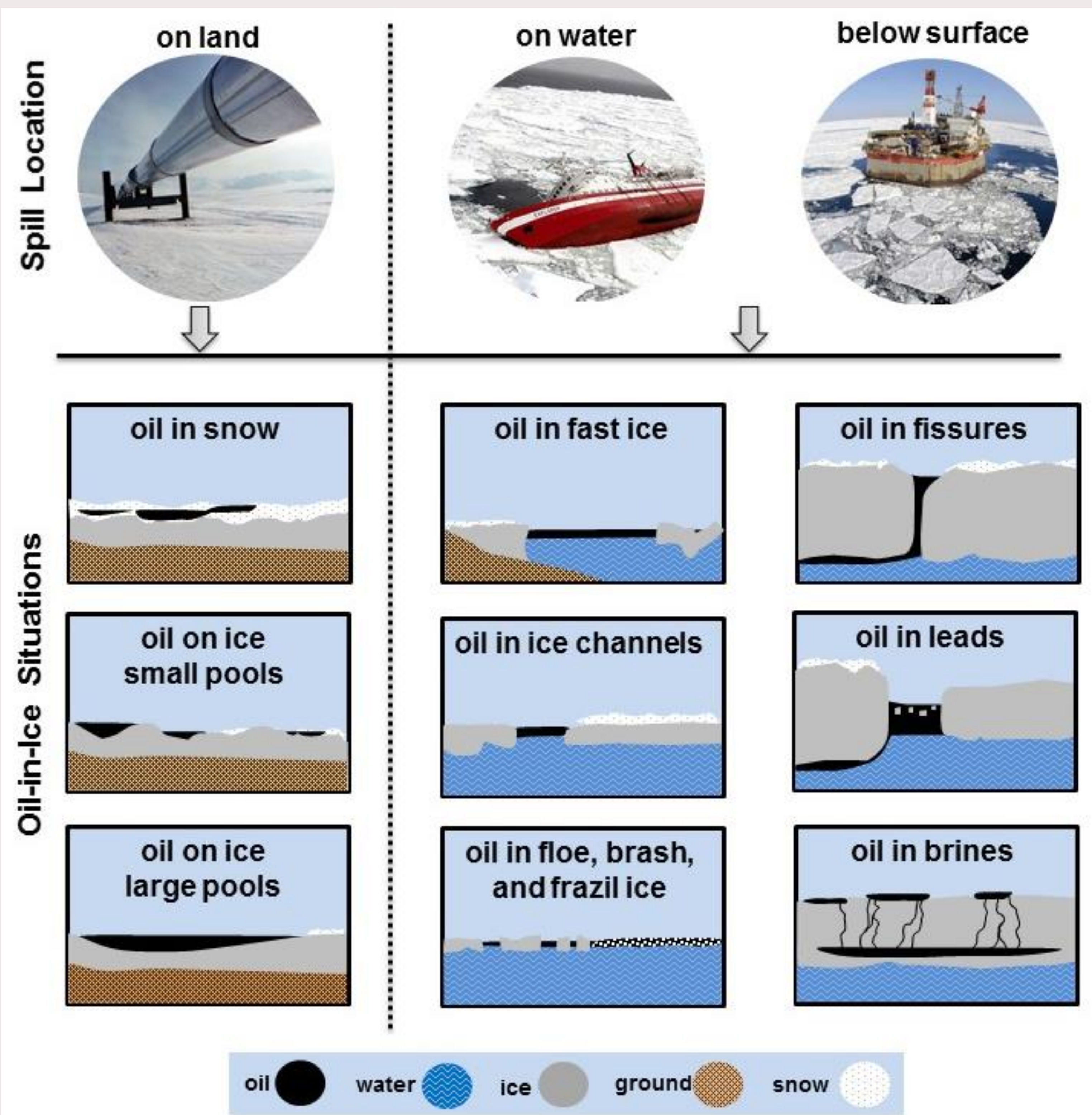
Motivation

Cleanup of oil spills in the Arctic



***In situ* burning as an effective and practical method for cleanup**

Figure 2. Burning of oil in pack ice.

Lateral Cavity Problem

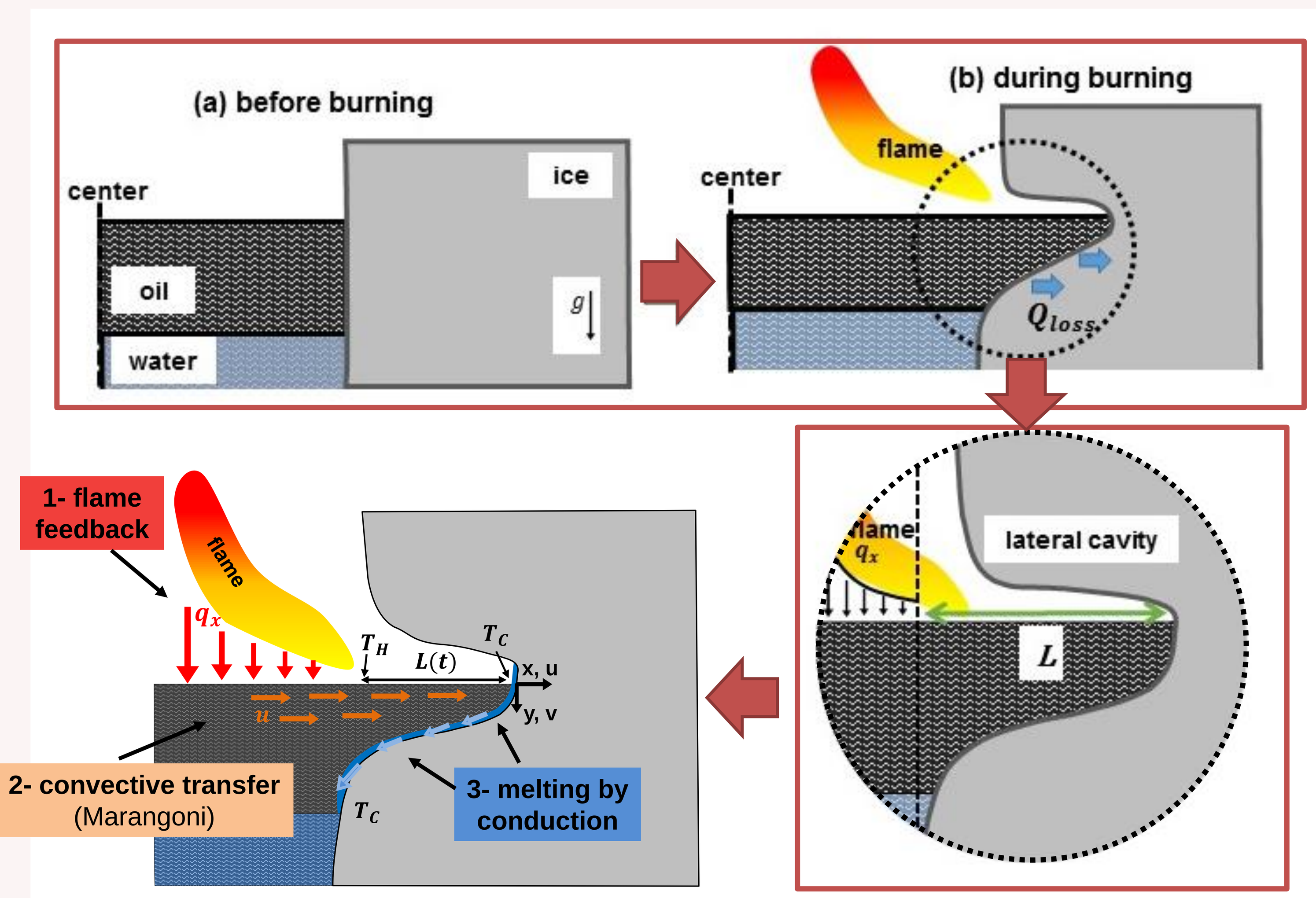


Figure 3. Cavity formation and the mechanisms that are involved.

Objectives of the Study

To develop a scaling model of the ice melting that occurs during in-situ burning.

Scaling with Order of Magnitude

1- $\dot{q}''_x = \chi\, \rho_\infty C_{p\infty}\left[T_\infty g\left(T_f - T_\infty\right)\right]^{\frac{1}{2}} D^{1/2}$

2-

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$\frac{\partial^3 u}{\partial y^3} - g\beta \frac{\partial T}{\partial x} = 0$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha \nabla^2 T$$

$$\text{B.C.}: \mu\frac{\partial u}{\partial y} = -\sigma_T \frac{\partial T}{\partial x}$$

3- $\rho_{ice} L'_{m,ice} U \frac{\partial y}{\partial x} = k\left(\frac{\partial T}{\partial y}\right)_{y=-\delta}$

Assumptions

1- Flame feedback may be quantified with pool fire diameter as shown in Equation 1.
2- Coordinate system is attached to the tip of the melting front which advances to the right with velocity U = L/t.
3- Intrusion layer is slender with thickness of δ<<L.
4- Liquid is assumed Newtonian with constant properties and a simplified form of momentum equations.
5- Marangoni is assumed to be the driving force of liquid therefore the boundary condition on the top surface of the liquid layer is considered for scaling. 5- Energy conservation for the melting interface may be written by Equation 3.

Order of magnitude scaling

$$T_H - T_C = \Delta T = \frac{\dot{q}''_x d}{k}$$

$$\frac{u}{\delta_2} \sim \frac{v}{\delta_1}$$

$$\frac{u}{\delta_1^{\,3}} \sim g\beta \frac{\Delta T}{\delta_2}$$

$$u\frac{\Delta T}{\delta_2}, v\frac{\Delta T}{\delta_1} \sim \alpha \frac{\Delta T}{\delta_1^{\,2}}$$

$$\text{And } \frac{u}{\delta_1} \sim \frac{-\sigma_T}{\mu}\frac{\Delta T}{\delta_2}$$

$$k\frac{\Delta T}{\delta_1} \sim \rho_{ice} L'_{m,ice} U \frac{\delta_1}{\delta_2}$$

Cavity intrusion length

$$L \sim \left(\frac{-\sigma_T}{\mu\alpha}\right)^{2/3} \left(\frac{\dot{q}''_x d}{k}\right)^{5/3} \left(\frac{kt}{\rho_{ice} L'_{m,ice}}\right)\left(\frac{1}{\delta_2}\right)^{1/3}$$

In dimensionless form:

$$\frac{L}{\delta_2} \sim (Ma)^{\frac{2}{3}}(Ste.Fo)$$

where $Ma = \frac{-\sigma_T \Delta T \delta_2}{\mu\alpha}$, $Ste = \frac{C_p \Delta T}{L'_{m,ice}}$, and $Fo = \frac{\alpha_{ice} t}{\delta_2^{\,2}}$ are the dimensionless numbers associated with the ice melting problem.

Assessment of Scaling

The available experimental data showing the intrusion length of oil in different studies were collected. The scaling correlation was adjusted to experimental data using least square regression method.

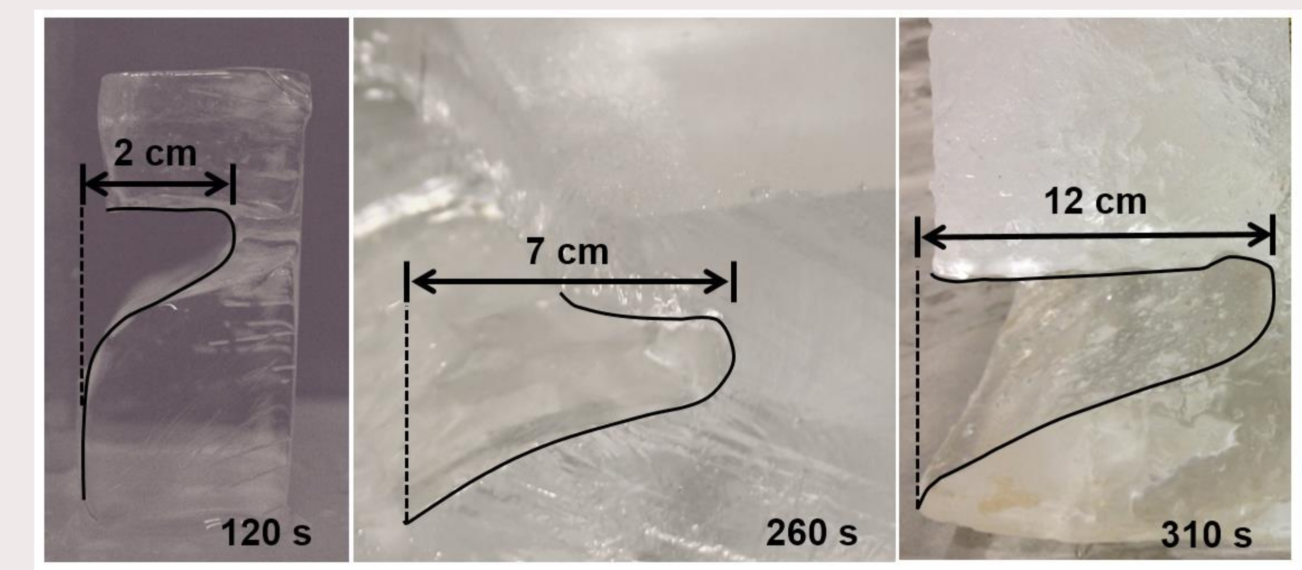


Figure 4. Examples of lateral cavity formation a) n-octane burning in a 10 cm square tray with an ice wall on the side , b) ANS crude oil burning in an ice channel of 60 by 16 cm, c) ANS crude oil burning in a 100 cm square.

Final Correlation:

$$L \sim 0.45 \left(\frac{-\sigma_T}{\mu\alpha}\right)^{0.14} \left(\frac{d\dot{q}''_x}{k}\right)^{1.18} \left(\frac{k_{ice} t}{\rho_{ice} L_{m,ice}}\right)^{0.84} \left(\frac{1}{\delta_2}\right)^{1/3}$$

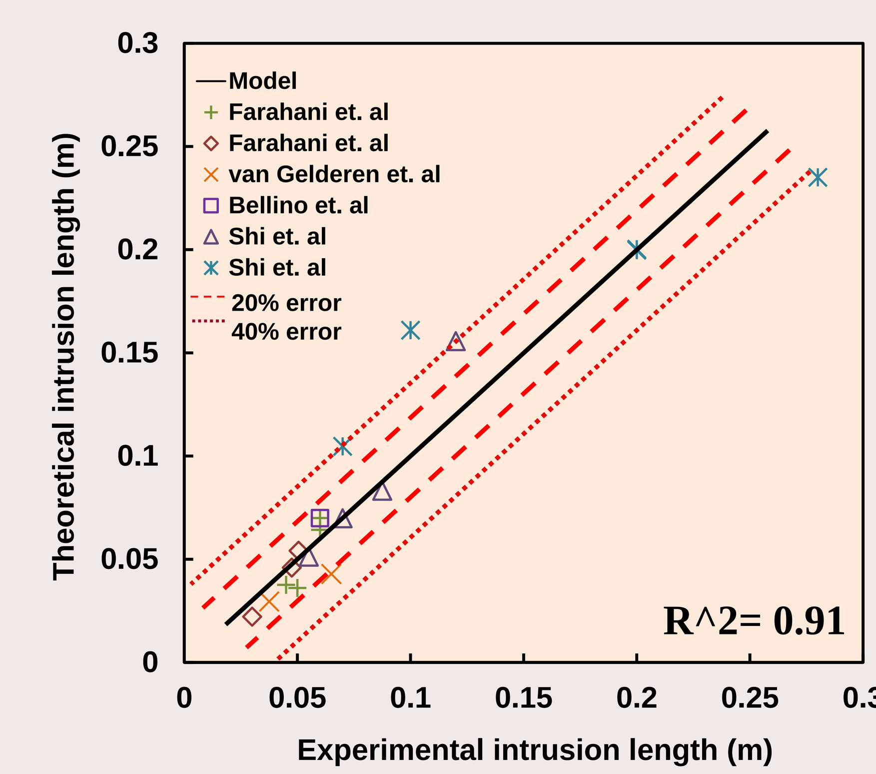


Figure 5. Comparison of the scaling analysis with experimental data.

Conclusions

1- The analysis considered the different physical aspects of the lateral cavity problem including the heat feedback from the flame to fuel surface, the convective transfer toward the ice, and the melting energy continuity of the ice wall.

2- The scaling of this problem has provided a predictive tool to estimate the intrusion length of lateral cavity problem which will be useful in evaluating the success of ISB operation.

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